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AUTONOMOUS FLIGHT CONTROL SENSING TECHNOLOGY (AFCST) PROGRAM PHASE I -- CAPABILITY GOALS AND SENSING REQUIREMENTS

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14. ABSTRACT

Lack of pilot vision and the resulting poor situational awareness has been a major limiting factor for unmanned air vehicles (UAVs) in terms of capability and safety. Tactical situation assessment includes evaluating such critical factors as weather, conflicting traffic, targets/threats and their locations, and perceiving spatial relationships to maintain formation or guide the aircraft through approach, landing, and subsequent terminal area operations. Obviously, this tremendously important capability represents a challenge for future UAV systems to operate in consonance with manned aircraft in both Federal Aviation Authority (FAA)-controlled airspace and military theaters where traditional visual flight rules (VFR) procedures are the norm. This paper describes AFCST Phase I program results, namely, prioritized future UAV capability goals and associated sensing requirements. AFCST sensor design drivers are also briefly discussed.

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***Abstract*:**

Lack of pilot vision and the resulting poor situational awareness has been a major limiting factor for unmanned air vehicles (UAVs) in terms of capability and safety. Tactical situation assessment includes evaluating such critical factors as weather, conflicting traffic, targets/threats and their locations, and perceiving spatial relationships to maintain formation or guide the aircraft through approach, landing, and subsequent terminal area operations. Obviously, this tremendously important capability represents a challenge for future UAV systems to operate in consonance with manned aircraft in both Federal Aviation Authority (FAA)-controlled airspace and military theaters where traditional visual flight rules (VFR) procedures are the norm. This paper describes AFCST Phase 1 program results namely prioritized future UAV capability goals and associated sensing requirements. AFCST sensor design drivers are also briefly discussed.

1. INTRODUCTION

Under the USAF-sponsored AFCST program, Northrop Grumman is investigating how "vision-based" guidance, navigation, and control (GN&C) technologies can be best used for improvements in performance, safety, and reliability for UAVs operating autonomously in FAA and theater airspace. The study is structured in three sequential

phases: 1) Phase 1 – Capability Goals and Requirements Specification, 2) Phase 2 - Preliminary Design, and 3) Phase 3 - Application Demonstrations. Figure 1 shows this three-phased approach and the expected results from each phase of the program. This paper describes the Phase 1 results, namely capability goals and associated sensing requirements. AFCST sensor design drivers are also briefly discussed.

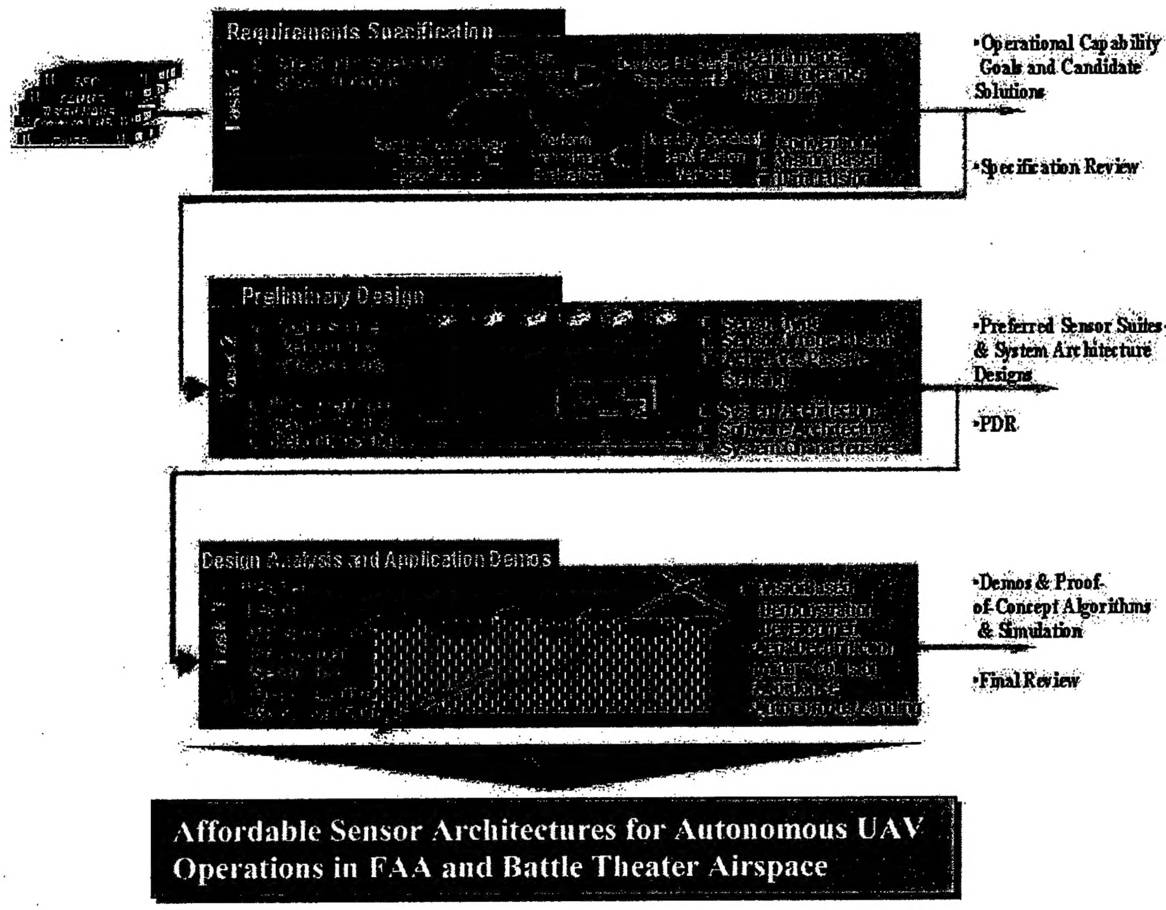


Figure 1 <u>Three-phased AFCST Approach And Expected Results</u>

The AFCST contract has been identified as one of the key technology development and maturation efforts for contributing to the objectives associated with probability of loss of aircraft (PLOA) and autonomous control level (ACL) [1,2]. Specifically, the AFCST program is to enhance "affordable" and "reliable" autonomous sensing technology such that the "observe" portion of the ACL scale can be greatly advanced for the types of missions envisaged for future combat UAVs. Performance and safety

enhancements through smart integration of multi-spectral multifunction vision sensors with conventional sensors must be accomplished to reach these goals.

2. PHASE 1 APPROACH

The iterative process involving five subtasks in Phase 1 to establish AFCST capability goals and sensing requirements is illustrated in Figure 2. Both the single-ship ISR type applications and the multi-vehicle combat UAV type of applications were used to identify applicable GN&C functions and their initial sets of operational capability goals in Subtask 1.1. At this point, the focus was primarily on capabilities for each standalone GN&C function. Quantitative sensing requirements were then developed in Subtask 1.2 and candidate sensors and data fusion methods were identified in Subtask 1.3. For the quick screening of preferred sensor suites in Subtask 1.4, the focus was then shifted from standalone GN&C functions to the merits of the overall vehicle. Based on the results of Subtask 1.4 and technology transition opportunities identified in Subtask 1.5, the operational capability goals previously identified were then reconciled and re-prioritized at the vehicle level.

The potentially synergistic sensor usage for multiple-functions has been very much emphasized from the beginning of the AFCST program. This potential was carefully examined, not only among various GN&C functions, but also between GN&C functions and mission functions.

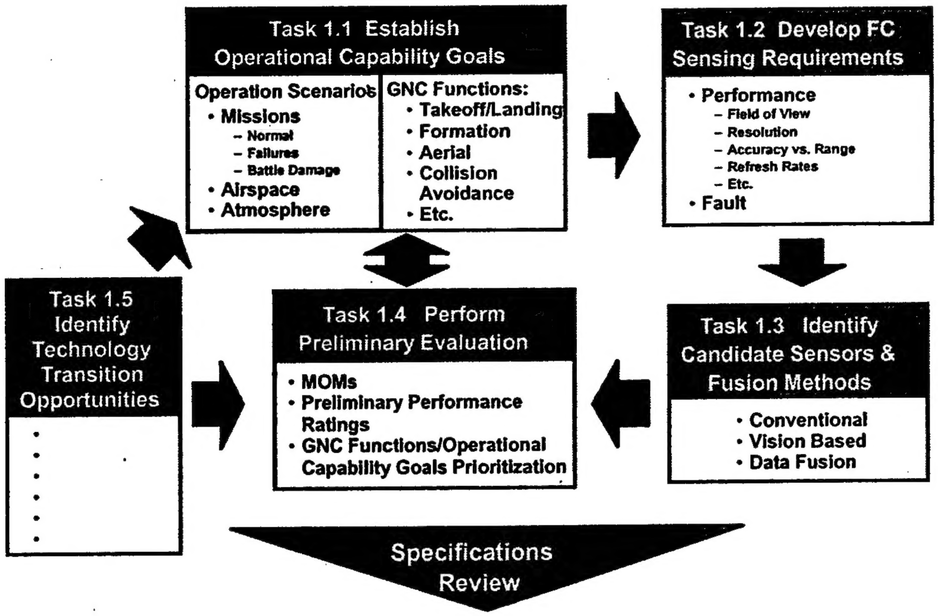


Figure 2 Phase 1 Approach – Capability Goals & Requirements Specification

A comprehensive list of GN&C functions, shown in Figure 3, were identified and analyzed with respect to near-term (NT), technology availability date (TAD) 2007, and far-term (FT), TAD 2013, applications. The idea of having two-stage requirements (i.e., NT and FT) came from the fact that a lower risk and yet more affordable sensor solution, and hence less aggressive requirements, would be highly desirable for cost sensitive UAVs or as an interim solution for future high performance UAVs. With lower-level NT goals set separately, the research team was then free to address higher-level goals and/or preferred solutions that would require new enabling sensor technologies. Note that the basic principle of being as good/safe as piloted aircraft was adopted for setting NT capability goals, However, this fundamental principle was modified for scenarios where the pilot's capability is deemed inadequate and/or little cost is added if additional capability is provided. This philosophy is analogous with the FWV approach of specifying Phase I and Phase II goals for the same TAD 2007 and 2013 respectively.

GN&C Functions	NT (TAD 2007)	FT (TAD 2013)
MAC Avoidance	Goals Set	Goals Set
Landing	Goals Set	Goals Set
Formation Flight	Goals Set	Goals Set
Ground Operations	Goals Set	Goals Set
Aerial Refueling	Goals Set	Goals Set
Weather Avoidance	Fall Out	Fall Out
Air Intercept Avoidance	Fall Out	Goals Set
Terrain & Obstacle Avoidance	Fall Out	Fall Out
Missile Evasion	Fall Out	Goals Set

Figure 3 GN&C Functions & Prioritization

Note that in Figure 3 the first five GN&C functions, mid-air collision avoidance (MACA), autonomous landing (AL), formation flight (FF), ground operation (GO), and autonomous aerial refueling (AAR), are considered primary. Specific NT and FT requirements were established for each of these five functions. The other four functions are considered secondary. Weather avoidance is likely to be accomplished mostly through mission planning. Short-range weather detection and autonomous evasion would be beneficial and hence sensing requirements were treated as a fall out.

Both air interceptor avoidance and missile evasion would be desirable for enhancing survivability. These two can actually be classified as mission functions as opposed to GN&C functions and both would require expensive all-aspect long-range sensors. Only specific requirements were established for FT as there is strong synergism with other GN&C functions. Terrain and obstacle avoidance were also treated as fall outs since both types of UAV applications do not require low altitude flight. Like weather avoidance, terrain and obstacles are to be avoided through proper mission planning. On-board detection and autonomous evasion would still be required, but would not drive sensing needs. Note that vision-based navigation would be highly desirable to supplement inertial

and satellite navigation. This is treated as a sub-mode to autonomous landing as it has the most stringent accuracy and update rate requirements.

Due to limited length of this paper, only the five primary GN&C functions are discussed hereinafter.

3. CAPABILITY GOALS

Mid-Air Collision Avoidance (MACA). This subsection addresses the "see and avoid" problems and recommended NT and FT goals. It is important to note that "cooperative systems" such as the current Traffic alert and Collision Avoidance System (TCAS) and/or the emerging Automatic Dependent Surveillance – Broadcast (ADSB) would be preferred as they provide more information more accurately from a longer distance. However, as the word cooperative implies, these systems do not provide any protection if the other aircraft does not carry compatible equipment. This is unfortunately the current situation in the United States and many parts of the world. For example, small general aviation (GA) aircraft are exempted from carrying TCAS in the United States when flying VFR in uncontrolled airspace.

FAA [3-6] and military [7,8] mishap data were studied first to understand current problems with manned systems. Figure 4 shows some recent FAA statistics on near mid air collision (NMAC) from 1994 to 1999. Note that as expected, GA is the biggest culprit, but all aircraft types are involved. It is somewhat surprising that NMAC involving commercial aircraft carrier (A/C) to commercial A/C ranked 5th during this period. Some additional noteworthy facts collected during this study are as follows.

- A total of 152 midair collisions (MAC) occurred in the United States from 1978 through October 1982, resulting in 377 fatalities;
- The yearly statistics remained fairly constant throughout this 5 year period
- During this same time period there were 2,241 reported NMACs;
- Statistics indicate that the majority of these midair collisions and near midair collisions occurred in "good weather" and during the hours of "daylight";
- FAA has since introduced several programs with a greater emphasis on the need for recognition of the human factors associated with midair conflicts;

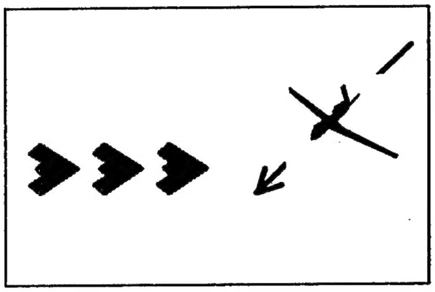
- Since 1987, measures taken by FAA and airline industry have shown steady improvements in MAC and NMAC.

Operator Type	1994	1995	1996	1997	1998	1999	
A/C – A/C	28	23	20	17	15	17	5
A/C – G/A	47	43	35	49	44	44	1
A/C – Military	11	13	8	20	12	11	
A/C – Other	7	5	3	6	2	5	
A/C – Unk/NR	49	28	22	35	25	31	3
G/A – G/A	40	39	37	33	31	42	2
G/A – Mil	20	28	21	23	10	17	6
G/A – Other	7	7	5	0	3	3	
G/A – Unk/NR	31	24	27	34	29	32	4
Mil – Military	8	7	1	3	5	12	
Mil – Other	1	0	1	1	0	1	
Mil – Unk/NR	22	17	14	8	28	25	7
Oth – Other	0	1	0	0	0	2	
Oth – Unk/NR	4	3	0	4	3	4	
Unk – Unk	0	0	0	5	1	6	
Totals	275	238	194	238	208	252	

- **GA Is the Biggest Culprit, but All Aircraft Types Had Been Involved Including A/C to A/C (Ranked #5)**

Figure 4 FAA Near Mid-Air Collision (NMAC) Data by Aircraft Type

Given the statistics and many lessons learned, Figure 5 summarizes the AFCST NT and FT capability goals for MACA. Note that, in this case, human eyes, brain processing of image data, and cockpit visibility constraints have collectively proven to be hardly adequate for the job. The NT capability goals, as set in Figure 5, are intended for a "good" job and definitely "better than" a human pilot in many aspects. These goals were, however, carefully chosen so as not to impose too many problems for near-term available sensing technologies. For example, detection of a small aircraft from 6nm is required to provide 60 seconds lead for evasion maneuvers assuming a 360 knots closure rate (ownship and threat are both at 180 knots). To do so in day and night would definitely be beneficial, but within the capabilities of today's high performance infrared (IR) sensor. To track up to 50 aircraft would also be advantageous and achievable with today's computer power. On the other hand, having 4-pi and all-weather sensor coverage would drive toward a near-perfect MACA solution, but with much higher attendant cost and weight. These higher goals are, then, reserved for FT.



Assumptions:
- **Need to avoid collision with cooperative and non-cooperative flying objects in mixed operation environment**
- **Standard mission equipment include TCAS II & ADS-B**

- **NT (TAD 2007)**
  - **Simultaneous detect and observation of small aircraft (up to 50) from 6nm**
  - **FOV/FOR comparable to piloted aircraft, but with enhanced protection against overtaking slower aircraft**
  - **Full autonomy (i.e., autonomous detection, avoidance, and recovery)**
  - **3 statue miles VMC**
  - **Day and Night**
  - **See and avoid equipment to supplement/integrate with TCAS II & ADS-B**
  - **Ability to detect and safely recover from single equipment failures**
- **FT (TAD 2013)**
  - **4pi coverage up to 100 flying objects**
  - **IMC (25 mm/hr rain)**

Figure 5. AFCST MACA Capability Goals

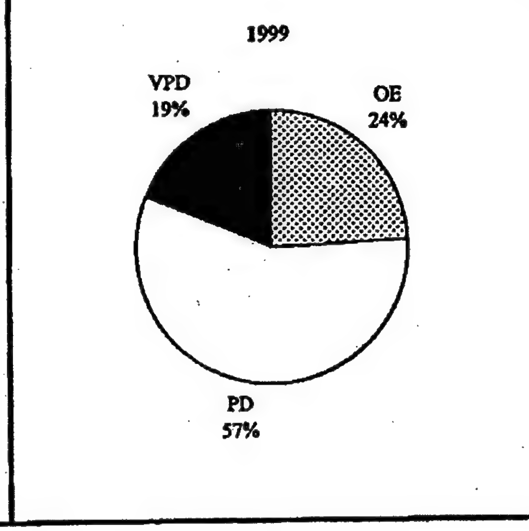
Ground Operation (GO). Similar to the MACA case, FAA runway incursion (RI) mishap data [9, 10] were studied first. This can be seen as "see and avoid" problems on the ground. Figure 6 shows the incident data in 1999 broken out to three major sources of the problem: pilot deviations (PD), operator errors (OE), and vehicle pedestrian deviations (VPD). As shown in Figure 6, PD has been by far the biggest problem. Some other interesting facts collected from the study are as follows.

- Pilot taxing onto runways or taxiways without clearance in 62% of cases
- Pilot landing or departing without clearance in 23% of cases
- Pilot landing on wrong runway in 10% of cases
- Pilot distraction in 17% of cases
- Pilot disoriented or lost in 12% of cases
- Pilot not being familiar with ATC procedures or language in 22% of cases
- Pilots not familiar with airport in 19% of cases
- GA aircraft in 69% of cases
- Low time pilots (less than 100 flight hours) in 32% of cases
- High time pilots (greater than 3000 flight hours) in 10% of cases

- The top 5 aircraft involved in runway incursions were all single-engine GA aircraft.

1999

MONTH	Incident Type OE	PD	VPD	TOTAL
January	8	17	4	29
February	7	9	5	21
March	3	8	6	17
April	4	15	3	22
May	8	18	3	29
June	7	12	9	28
July	7	23	9	39
August	7	13	3	23
September	8	17	8	33
October	7	13	4	24
November	7	15	3	25
December	5	22	4	31
TOTAL	78	182	61	321



Runway incursion data is based on preliminary reports and is subject to change following a final investigation.
Source: Runway Safety Program Office, ATP-20

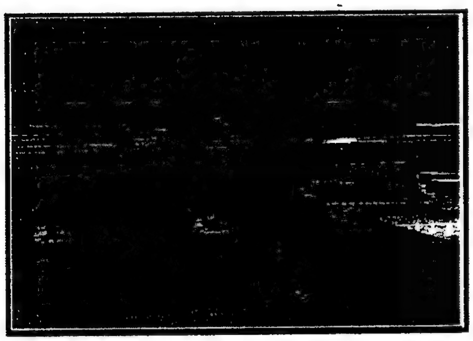
Note: - OE = Operator Errors
PD = Pilot Deviations
VPD = Vehicle Pedestrian Deviations

Figure 6. FAA Runway Incursion Incident Data (Year 1999)

It should be noted that the above "pilot problems" can still occur for UAVs due to problems with sensors, autonomy software, UAV ground operators, or a combination thereof. However, some of the "human factor problems" such as not being familiar with or following ATC procedures, are obviously different for UAVs and could be easily solved.

Following the same thought process, the AFCST GO capability goals were established as summarized in Figure 7. Note that for NT applications, differential global positioning system (DGPS) is solely used for following taxi routes/stops either pre-planned or provided in real time by ground operators. Vision sensors are then used to detect runway incursions and execute evasive maneuvers autonomously if necessary. This would be extremely advantageous for ground operator workload reduction and thus enable a high UAV-to-operator ratio. In the event that DGPS is not available due to equipment failures or jamming, the UAV must stop and wait to be towed or resort to

other backup means. To use vision sensors for taxing would require extremely high sensor resolution for sign and marking reading/pattern recognition and the ability to differentiate colors. This, along with all-weather capability, are considered "stretches" and, hence, reserved for FT.



Assumptions:

- High autonomy for UAV -to-operator
- Taxi sequentially takeof
- Taxi autonomously DGPS planned route operator capabilit

- NT (TAD
  - Autonomously detect and avoid runway incursions and unsafe separation
  - Follow Operator/MCS selected taxi route/stops with DGPS. Ground operator monitors only for up to 4UAVs .
  - Manual parking
  - 3 statue miles visibility (Weather State 2 @ sea level)
  - Day and night
  - Fail safe
- FT (TAD
  - Autonomous execution of taxi route/stops, verify markings, detect and avoid runway incursions
  - Weather State 5 @ SL (100 ft ceiling, 1200 ft RVR of visibility, and 25 mm/hr rain)
  - Able to operate with jammed GPS
  - Fail safe

Figure 7 AFCST GO Capability Goals

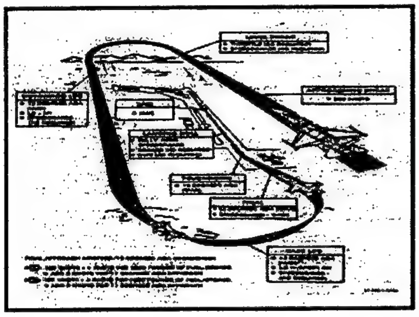
Autonomous Landing (AL). Occassionally, there are news reports of a pilot having engine problems and landing his airplane safely on an open highway or cornfield. This may be the ultimate autonomous landing capability for UAVs, but as one can imagine, there are many possible and yet useful intermediate points. To facilitate the specification of capability goals, airports and/or landing fields were first classified in five levels and their key attributes, which would impact UAV sensor requirements for autonomous landing, were identified as shown in Figure 8. Note when a "P" is labeled, it is considered "not available" for the purpose of the AFCST program.

Landing Site Capability	Airfield/Airport with Increasing Order of Sophistication				
	Unprepared Airfield	GA/VFR	Forward Mil Airbase	IFR	Large Comm. Airport
Surveyed Data DTED, Runway Param, etc.)	×	✓	✓	✓	✓
Runway Marking	×	✓	✓	✓	✓
Runway Lighting	×	P	✓	✓	✓
Control Tower/ Published Approach	×	P	P	✓	✓
Glide Slope/Localizer	×	×	P	✓	✓
ATC Radar	×	×	×	✓	✓
DGPS/JPALS/WAS	×	×	✓	P	✓
Ground Control Radar	×	×	×	×	P

Notation: × = No, ✓ = Yes, P = Maybe

Figure 8 Key Airport Attributes for Autonomous Landing

With the above airport/airfield definitions, the AFCST AL capability goals are summarized in Figure 9. A key decision embedded in these goals is that unlike a human pilot, the UAV can most easily navigate and land through inertial means. This inertial landing as opposed to visual landing is, therefore, retained as the primary method. The use of vision sensors is then focused as additional navigation aids, situational awareness, and to reduce the dependency on airport/airfield equipment and/or priori data. For NT goals, the challenges involve performance in a GPS jammed environment and with adequate fault tolerance, namely fail operational (FO) performance. For FT goals, the airport/airfield equipment, runway markings, and priori data such as the required published approach, are totally eliminated except for survey data (i.e., terrain elevation and culture features). All weather capability is, as usual, included as part of the FT goals.



Assumptions:
- Follow Existing Airport/Airfield Procedures

- NT (TAD 2007)
  - Able to Operate out of any Towered Airport with Published Approach and survey data
  - Autonomous execution of En Route, Approach, ID & Assess Runway, Descend, and Land
  - VFR visibility (3nm statue miles horizontal and 1,500 ft ceiling)
  - 30 knots cross-wind @ 120 knots landing speed
  - Able to land with jammed GPS
  - Fail-Op
- FT (TAD 2013)
  - Able to Operate out of Untowered Airfield with survey data, but without Published Approach
  - Weather State 5 @ SL (100 ft ceiling, 1200 ft RVR of visibility, and 25 mm/hr rain)
  - Fail-Safe for weather capability

Figure 9. AFCST AL Capability Goals

Formation Flight (FF). Military formation flight grew out of the necessity to operate aircraft in coordinated teams of two or more, either because a single aircraft was more vulnerable or because a group of aircraft was more effective. Pilots in WWI, for example, soon learned that the lone wolf in air combat was very vulnerable to surprise, and, even if not surprised, it was difficult to survive if outnumbered. This was true of both fighters and bombers. They also learned that flying a group of aircraft in close proximity, as is necessary if they are to be close enough to render assistance in a fight, poses its own set of problems. If the group needs to fly together, they need to takeoff close together, which can create congestion and confusion on the ground. Once airborne, pilots must stay close together without running into one another while looking out for the enemy and monitoring their own aircraft's operation. After the mission, the aircraft must recover and land. Naturally each vehicle will be short of fuel and, some may have battle damage, so getting the whole group of aircraft down quickly and efficiently is important. Weather, of course, makes the whole operation more difficult because of reduced visibility. Add to all of this the need to accomplish the mission in spite of aircraft and communications malfunctions and it can be seen that formation flying is not a casual task.

Formation flight needs, and hence capability goals for UAVs, are not a trivial issue. In AFCST, typical piloted formation flights such as close formation, route formation,

spread formation, and extended trail formation [11] were analyzed first with respect to UAV implementation. Figure 10 shows example analysis results for spread formation and some interesting flying techniques for turning that pilots have to learn through training.

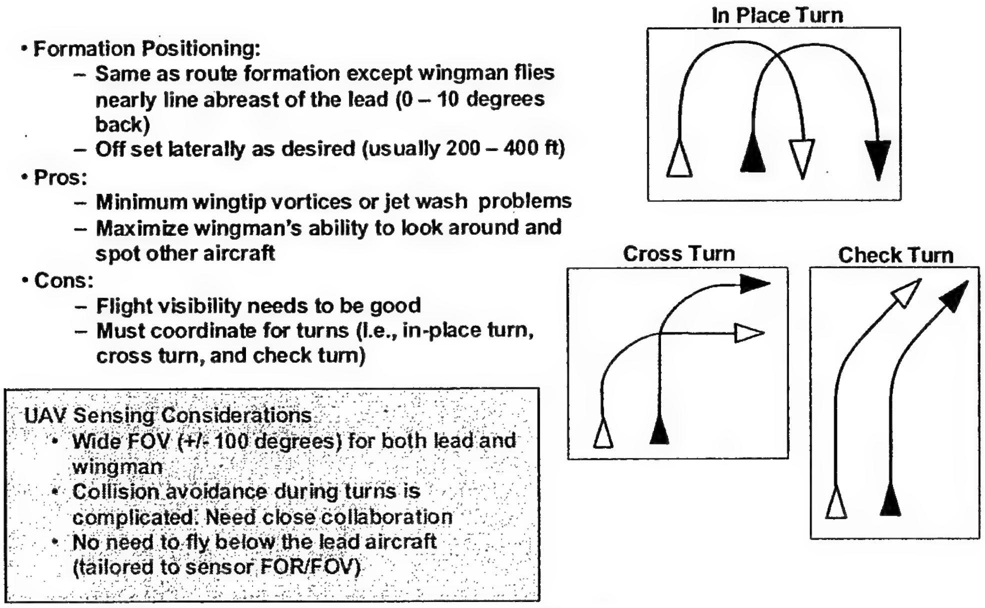


Figure 10. Analysis of Lateral Spread Formation

The aforementioned UAV implementation assessment was then followed by a military utility assessment by evaluating it against a number of concepts of operation including suppression of enemy defense (SEAD), cooperative emitter location, cooperative strike, and cooperative surveillance and targeting for advanced combat UAVs. The resulting AFCST FF capability goals are summarized in Figure 11. It is worthy pointing out that only a couple of formations (i.e., straight/staggered trail for *enroute* and lateral spread for combat area) and no ad hoc maneuvers are determined realistic, but adequate for NT. For FT, it is a stretch to fly with manned aircraft, to fly more UAVs together in closer proximity, in more severe turbulence, and to complete missions through graceful degradation in the presence of failures. Note that in this case all weather capability is not included for FT. This is because in the advanced UAV concepts of operation, formation flights are to be executed at high altitudes where weather or visibility are not major issues.

Assumptions:

- **Up to 8 UAVs in a Group**
- **When Flying with Piloted Aircraft, UAVs will follow commands from Piloted Aircraft**

- **NT (TAD 2007)**
  - **Up to 4 UAVs in a flight; No mixed manned/unmanned operation**
  - **UAV optimized straight/staggered trail for enroute plus lateral spread in combat area**
  - **Minimum separation (200 feet wingtip to wingtip, 400 feet nose to tail, and 50 feet vertical)**
  - **"One-at-a-time" pre-determined procedures for forming & changing formations**
  - **3nm Visibility, Light turbulence (Weather State 2 @ 25K ft altitude)**
  - **Day and Night**
  - **Abandon formation when primary position sensor Not Available (I.e., fail safe; ability to detect critical failures)**
  - **Operable in GPS jammed environment**
- **FT (TAD 2013)**
  - **Up to 8 UAVs in a flight; Routine Formation with Manned Platforms**
  - **Minimum separation (100 feet wingtip to wingtip, 100 feet nose to tail, and co-altitude);**
  - **3nm Visibility, But Moderate turbulence**
  - **Adjust formation parameters when primary position sensor degraded (I.e., fail degraded)**

Figure 11. AFCST FF Capability Goals

Autonomous Aerial Refueling (AAR). The most desirable and perhaps most challenging method for refueling UAVs is to employ a technique similar to piloted aircraft. This will allow refueling operations to be accomplished in a mixed aircraft operation environment, thus retaining a high degree of operational flexibility while imposing minimum impacts to existing systems.

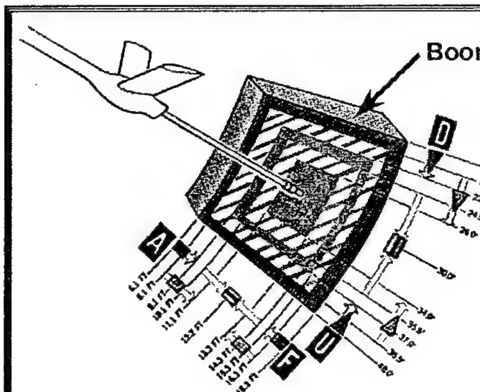
With the above goal in mind, Figure 12 shows various stages and associated tasks for a piloted aircraft capable of performing the USAF style of boom aerial refueling. The two middle tasks of join-up and boom refueling are probably most demanding where the receiver aircraft needs to approach the tanker slowly at first and then hold the relative position extremely tightly. Figure 13 shows such tight position control requirements for a KC-135. Note that the desirable values are set at levels considerably smaller than the boom limits for an adequate safety margin. Also note that 20% of the allowable position errors are allocated to UAV relative position sensor errors, resulting a 0.5 feet circular error probability (CEP) accuracy requirement. When compared to a human pilot, this is not nearly as accurate as a human pilot's observation capabilities. However, most aerial refueling challenges result from aerodynamic interaction (i.e., tanker wakes) and a pilot's

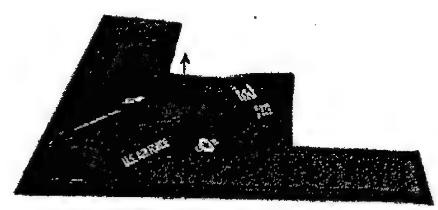
ability for high rate precision controls. It is, therefore, judged that 0.5 feet CEP would be a reasonable starting point for sensing requirements.

Rendezvous with Tanker →	*Join-up* →	*Boom Refueling* →	*Post-Refuel Maneuvers*
• Determine ARIP (location and arrival time) • Generate and Follow a 4D Trajectory • Select and Change to AAR RZ Formation • Locate and ID Tanker • Select Intercept Procedure	• Establish Communication • Execute Join-up • Determine Refuel Order • Move to Pre-Contact Position • Receive Clearance to Contact from Boom Operator • Move to Contact Position • Verify Contact	• Hold Position within Boom Limits • Verify Fuel Transfer Start • Verify Fuel Transfer Stop and Quantity • Initiate and/or Verify Disconnect • Respond to Breakaway Commands • Assess Operability	• Move to Post Refueling Formation Position • Depart Tanker Formation • Ensure Safe Separation from Tanker • Update Mission Plan

Through Out All Phases:
- Maintain Situation Awareness, Identify Unsafe Positions/Maneuvers
- Manage Contingency/Emergency
  - –Collision Avoidance & Recovery
  - –Emergency Breakaway & Recovery

Figure 12 Boom AAR Top-down Task Assessment





UCAV Motion		
Direction	Desired ± Ft.	Limits ± Ft.
δx	2.0	6.9
δy	2.0	6.9
δz	2.5	8.4

"If you can make speed adjustments on the order of two knots and position adjustments on the order of two feet, then you can do the task."

- KC-135 Boom Limits Set the UAV Position Control Requirements
- 20% of Allowable Position Errors Allocated to Sensing Accuracy
  ➔ 0.5 ft CEP

Figure 13 Boom Refueling Receiver Aircraft Position Control Requirements

Figure 14 summarizes AFCST AAR capability goals. It should realized that a highly desirable goal would be no tanker modifications or adaptations. It is conceivable that certain capabilities can be added to the tanker to help reduce the required UAV sensing and/or autonomy level, but these add-on features must be able to be deactivated for refueling piloted aircraft. Also note that substantial goals are included for NT. For FT, the areas to pursue are: 1) closer refuel formation for quicker cycle time, 2) execution in moderate turbulence, 3) better control precision, and 4) graceful degradation in the presence of failures..

Assumptions:

- Operational Concept Similar to USAF Piloted Aircraft (I.e., no UAV to UAV)
- Use Existing USAF Tanker Capabilities with Minimum Modifications
- Terrain and Threat are Non - issues

- **NT (TAD 2007)**
  - X-on-1 (receiver aircraft UAVs only, no mixed operation with piloted receiver aircraft)
  - Standard piloted refuel procedures, no *ad hoc* procedures
  - UAV optimized refuel formation
  - No boom and tanker modification
  - Autonomous execution of -up
  - 3nm Visibility, Light turbulence (Weather State 2 @ 25K ft altitude)
  - Day and Night
  - As good as piloted aircraft in position/closure rate control
  - Abandon AAR if Comm or Position Sensor Degraded (I.e., Fail Safe; Ability to Detect Critical Failures)
  - Operable in GPS jammed
- **FT (TAD 2013)**
  - Closer refuel formation (100 ft nose to tail) to reduce cycle time
  - 3 nm Visibility, But Moderate Turbulence
  - Better than piloted aircraft in position/closure rate control (I.e., double the precision)
  - Modify AAR procedure if Position Keeping Degraded (I.e., fail degraded)

Figure 14. AFCST AAR Capability Goals

4. SENSING REQUIREMENTS AND DRIVERS

The capability goals described in Section 3 were mostly qualitative. These "qualitative goals" were translated into "quantitative vision sensing requirements" using a combination of computer simulations, pilot interviews, performance calculations, and literature/government regulation reviews. This was necessary to establish a sound foundation for evaluating and developing AFCST preferred sensor suites in Phase II.

The AFCST vision sensing requirements were established with respect to a set of metrics, namely field of view/field of regard (FOV/FOR), data type and accuracy, data rate, weather, criticality, and emission constraints. This was done initially function by function and then rolled up to the vehicle level by combining the worst-case requirements from each GN&C function. Here it is obviously assume that all GN&C functions will have to be performed during some portion of the UAV missions. The NT AFCST sensing requirements are summarized in Figure 15. Note that a requirement traceability is evident here as one can identify where and which G&C function drives the overall vehicle requirements. If a certain GN&C function is not needed, the reader can then easily roll up a new set of vehicle-level requirements.

Sensing Reqt's	Formation	AAR	MACA	AL	GO	Overall Vehicle
FOV	AZ: 30° EL: 30°	AZ: 60° EL: 30°	AZ: 30° EL: 30°	AZ: 60° EL: 25°	AZ: 60° EL: 25°	AZ: 60° EL: 30°
FOR	AZ: +/- 100° EL: +/-30°	AZ: +/- 100° EL: 30°, -10°	AZ: +/- 100° EL: 25°, -40°	AZ: +/- 60° EL: 10°, -45°	AZ: +/- 90° EL: 10°, -90°	AZ: +/- 100° EL: 30°, -90°
Data Type & Accuracy	• Ranging: 2 ft CEP @ 200 ft • Image: Wingman @ 3 nm	• Ranging: 0.5 ft CEP @ 100 ft • Image: Tanker @ 3 nm	• Ranging: 700 ft CEP @ 6 nm	• Ranging: 27 ft lat/ 5ft vertical @ 2,000 ft • Image: Person, small GV, & runway edges	• Ranging: 10 ft CEP @ 2,000 ft • Image: Person, small GV, & runway edges	• Ranging: 0.5 ft CEP @ 100 ft; 700 ft CEP @ 6nm • Various Images from 30 ft to 3 nm
Data Rate	30 Hz	30 Hz	1 Hz	1 Hz	1 Hz	30 Hz
Weather	VMC	VMC	VMC	VMC	VMC	VMC
Criticality	Mission Critical	Mission Critical	Safety Critical	Safety Critical	Safety Critical	Safety/Mission Critical
Emission Constraints	Wingman Safety	Tanker & Boom Operator Safety	Airport EMI Reqt's	Airport EMI Reqt's	Airport EMI Reqt's	Various Limitations

Figure 15 NT AFCST Vision Sensing Requirements

Given the NT AFCST requirements established above, it is interesting to draw the differences between the traditional "long-range targeting" type of mission sensors and these "situation awareness" type of autonomous GN&C sensors. The main NT AFCST sensor features required are:

- Very wide FOV/FOR
- Accurate ranging from short (100 feet) to medium distance (6 nm)
- ATR from short to medium distance
- High update/refresh rate (up to 30 Hz)
- Forward imaging
- Visual Meteorological Condition (VMC), 3nm visibility
- Safety and mission critical
- Various limitations on active sensing

One may appreciate the above differences more easily if it is pointed out the fact that traditional mission sensors are designed to only "assist" a pilot's vision and yet AFCST sensors are to "replace" a pilot's vision. It should also be pointed out that "long-range targeting" sensors would still be required for UAVs to perform its design missions and they may not be replaced by AFCST sensors. However, the goals should always be to look for intelligent integration opportunities for the greatest benefits at the overall system level.

Following the same process, "quantitative" FT AFCST vision sensing requirements were established as shown in Figure 16. Note that two additional functions, air interceptor avoidance (AIA) and missile evasion (ME), are included. Due to the length limitation of this paper, these two functions are discussed only briefly. The main FT AFCST sensor features required are:

- 4 Pi FOR
- Accurate ranging from short to medium to long distance
- ATR from short to medium to long distance
- Forward imaging
- High update/refresh rate
- VMC & Instrument Meteorological Condition (IMC)
- Safety and mission critical
- Various limitations on active sensing.

Note that the all-aspect (i.e., 4 pi), long-range (20 nm), and all-weather requirements are all extremely demanding. New enabling sensor technologies, smart sensor hardware and software integration will certainly hold the key to their eventual realization.

Sensing Reqt's	Forma-tion	AAR	MACA	AL	GO	AIA	ME	Overall Vehicle
FOV	AZ: 30° EL: 30°	AZ: 90° EL: 45°	AZ: 30° EL: 30°	AZ: 90° EL: 30°	AZ: 90° EL: 30°	AZ: 30° EL: 30°	4 Pi	4 Pi
FOR	AZ: +/- 120° EL: +/ -30°	AZ: +/- 120° EL: 45°, -25°	AZ: +/- 100° EL: 25°, -40°	AZ: +/- 90° EL: 10°, - 45°	AZ: +/- 110° EL: 10°, - 90°	AZ: +/- 120° EL: 30°, - 45°	4 Pi	4 Pi
Data Type & Accuracy	• Ranging : 0.5 ft CEP @ 100 ft • Image: Wingman @ 3 nm	• Ranging : 0.25 ft CEP @ 100 ft • Image: Tanker @ 3 nm	• Ranging : 350 ft CEP @ 6 nm	• Ranging: 13 ft lat/ 2.5ft vertical @ 2,000 ft • Image: Person, small GV	• Ranging : 5 ft CEP @ 2,000 ft • Image: Runway markings, signs	• Threat detection & ID at greater than 20nm	• Missile detection & ID at greater than 20nm	• Ranging: 0.25 ft CEP @ 100 ft; TBD ft CEP @ 20nm • Various Images from 30 ft to 20 nm
Data Rate	60 Hz	60 Hz	2 Hz	2 Hz	2 HZ	60 HZ	60 Hz	60 Hz
Weather	VMC	VMC	IMC	IMC	IMC	IMC	VMC	VMC/IMC
Criticality	MC	MC	SC	SC	SC	Surv. Critical	Surv. Critical	Safety/Mission/ Surv. Critical
Emission Const.	Wingman Safety	Tanker & Boom Operator Safety		Airport EMI Reqt's	Airport EMI	LPI		Various Limitations

Figure 16 FT AFCST Vision Sensing Requirements

5. SUMMARY

The AFRL-sponsored AFCST program is studying the critical UAV sensing needs for situation awareness which is typically performed by a pilot with his vision and vision aids. Northrop Grumman has assembled a team of experts in each of the requisite disciplines of UAV operation, sensors, autonomous controls, and aircraft integration via an IPT structure. This paper presents the Phase 1 results of capability goals and associated sensing requirements for NT (TAD 2007) and FT (TAD 2013) applications. Both single-vehicle ISR applications and multi-vehicle combat UAV type of applications were analyzed to identify applicable GN&C functions and their advantageous features. The resulting AFCST sensing requirements are uniquely different from those of the traditional long-range targeting sensors designed for piloted aircraft. New enabling

sensor technologies and intelligent sensor hardware and software integration will hold the key to the eventual realization of these goals. The capability goals and sensing requirements developed in AFCST Phase 1 set a good foundation for the Phase 2 efforts of preliminary preferred sensor suites design.

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REFERENCES

[1] Clough, B., "Autonomous UAV Control System Safety – What Should It Be, How Do We Reach It, And What Should We Call It?" NAECON 2000 Paper, October 2000.

[2] Clough, B., "Metrics, Schmetrics! How Do You Track UAV's Autonomy?" AIAA-2002-3499, AIAA 1st Unmanned Aerospace Vehicles, Systems, Technologies, and Operations Conference, Portsmouth, Virginia, May 2002.

[3] "Advisory Circular AC 90-48C (Pilot's Role in Collision Avoidance," FAA, U.S. Department of Transportation

[4] FAA-P-8740-51 FAA Accident Prevention Program

[5] FAA Aviation Safety Data, FAA Website

[6] NTSB Aviation Safety Data – NMAC Database, Department of Transportation

[7] Jet Safety.com – F-16 Crash Site, Updated 28 July 2001

[8] Jet Safety.com – USN, USMC, USA Data, March 1999

[9] "FAA Runway Safety Report, 1997-2000," June 2001

[10] "Air Traffic Control," FAA Pub. 7110.65M, 12 July 2
001

[11] Fighter Aircraft Technical Orders, AFTTP 3 Series Documents, Regulations.